Revisiting the Triangulation Method for Pointing to Supernova and Failed Supernova with Neutrinos

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In view of the advent of large-scale neutrino detectors such as IceCube, the future Hyper-Kamiokande and the ones proposed for the Laguna project in Europe, we re-examine the determination of the directional position of a Galactic supernova by means of its neutrinos using the triangulation method. We study the dependence of the pointing accuracy on the arrival time resolution of supernova neutrinos at different detectors. For a failed supernova, we expect better results due to the abrupt termination of the neutrino emission which allows one to measure the arrival time with higher precision. We found that for the time resolution of $\pm$ 2 (4) ms, the supernova can be located with a precision of $\sim 5\ (10)^\circ$ on the declination and of $\sim 8\ (15)^\circ$ on the right ascension angle, if we combine the observations from detectors at four different sites.

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I. INTRODUCTION

The observation of neutrinos coming from the next Galactic supernova (SN) driven by gravitational core collapse (hereafter, SN implies the one caused by the gravitational collapse) is expected to provide very interesting information on the dynamics of the process, namely, how these stars explode and form black holes, see e.g., [1, 2]. Moreover, it may also shed light on some unknown neutrino properties such as the neutrino mass ordering, see e.g., [3, 4].

Since neutrinos can break free from the dense region of the star from which photons cannot escape, they will be the first messengers from the sky to inform us the occurrence of the gravitational collapse. Indeed, it might be possible that the next Galactic SN cannot be located by optical observations due to obscuration. If so, observing neutrinos may be the only way to access its direction in the sky, apart from the possible simultaneous detection of gravitational waves [5].

The possibility of determining the direction of a Galactic SN by merely using its neutrinos, has been investigated in the past [6–12]. Most of the authors considered neutrino electron elastic scattering events in a water Cherenkov detector in order to determine the SN direction [6, 8, 10, 11]. According to Ref. [11], for a SN at 10 kpc, the pointing accuracy is $\sim 8^\circ$ at 95% C.L. if the Super-Kamiokande detector is considered. This can be further improved to $\sim 3^\circ$ if gadolinium is added to water [13], allowing to tag neutrinos from the inverse beta decay background. A megaton size water Cherenkov detector using this technique may be able to increase the pointing precision to $\sim 1^\circ$ [11].

On the other hand, the method of the arrival-time triangulation, previously discussed in Refs. [6–8], was readily dismissed due to the low precision on the arrival time of SN neutrinos expected mainly because the available detectors at that time were too small to register enough statistics for such a purpose.

We are now, however, entering a new era of large-scale detectors with IceCube currently working in the South Pole [14], the proposals of Hyper-Kamiokande in Japan [15] and of the European detectors which will be built in the Pyhäsalmi mine in Finland [16]. In view of this new trend, it is timely to revisit the usefulness of neutrino triangulation using big detectors in different continents, as suggested in Ref. [17].

According to [17], the IceCube detector can determine the arrival time of SN neutrinos with an uncertainty of $\pm$ 3.5 ms at 95 % C.L.. In the case of a so-called failed SN, where a black hole is formed while the neutrino flux is still measurably high [18], one expects the neutrino signal to terminate abruptly. As this sharp transition is expected to take place in $\lesssim$ 0.5 ms [19] the end-point of the neutrino spectrum can also be used for triangulation.

Since the observation of the arrival of SN neutrinos by various detectors will be a valuable tool to alert astronomers about the occurrence of the star collapse [20] allowing them to observe the light curve as early as possible or the formation of a black hole (in the case of a failed SN), it is important to explore different approaches to reconstruct the location of the SN as well as the failed SN in the sky.

II. TRIANGULATION METHOD

The distribution of SN in the Milky Way is expected to be concentrated in the Galactic disc. For the sake of discussion, let us consider the same SN distribution considered in Refs. [21, 22]. In Fig. 1 we show the expected SN distribution $f(\alpha, \delta)$, in the plane of equatorial coor-

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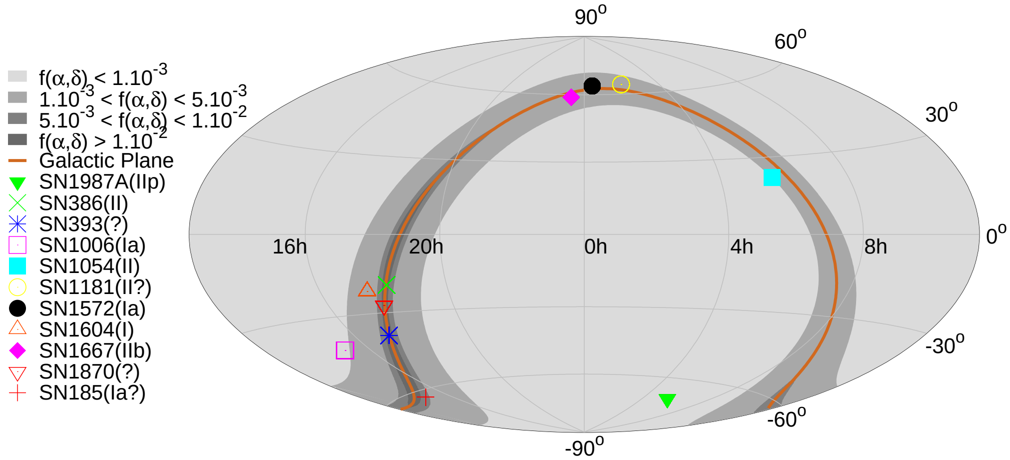

FIG. 1: Expected SN probability distribution $f(\alpha, \delta)$ based on the model considered in Ref. [21], shown in the plane of the equatorial coordinates $\alpha - \delta$ using the Hammer projection. Different contrast of the colors reflects the difference in probabilities as indicated in the legend. The position of the Galactic plane in the sky is indicated by the red curve. The location of the historical Galactic SN explosions are also shown with their type, when known, in parentheses.

dinates $\alpha - \delta$ where α and δ are, respectively, declination and right ascension, and $f(\alpha, \delta)\, d\alpha d\delta$ corresponds to the probability to find a SN in the interval of $(\alpha, \alpha + d\alpha)$ and $(\delta, \delta + d\delta)$ in the sky. The distribution function $f(\alpha, \delta)$ is normalized, as in [21] such that $\int d\alpha \int \delta f(\alpha, \delta) = 1$ with α and δ given in radian. In this figure, we also show the location of the historical Galactic SN and SN1987A explosions.

Let us consider two arbitrary detector sites $\boldsymbol{x_i}$ and $\boldsymbol{x_j}$ on the Earth and define the displacement vector as $\boldsymbol{d_{ij}} \equiv \boldsymbol{x_i} - \boldsymbol{x_j}$, and denote the SN direction in the sky by the unit vector $\boldsymbol{n}$. Then the difference of the arrival time of SN neutrino signals between two detectors, $\Delta t_{ij} \equiv t_i - t_j$, is given by

$$\Delta t_{ij} = \boldsymbol{d_{ij}} \cdot \boldsymbol{n}/c, \tag{1}$$

where c is the speed of light in vacuum. Here we will ignore the possible time delay due to the neutrino mass which can be estimated as

$$\Delta t_{\rm mass} \simeq 0.6 \left[\frac{D}{10\ \rm kpc}\right] \left[\frac{m_\nu}{0.1\ \rm eV}\ \frac{10\ \rm MeV}{E}\right]^2\ \rm ms, \tag{2}$$

where D is the distance to the SN and m_ν is the neutrino mass.

In this work, for the purpose of illustration of this method, we consider up to four different detector sites on the Earth, namely, Kamioka, South Pole, Pyhäsalmi and ANDES (Agua Negra Deep Experiment Site) [23] (see also [24]). It is because four is the minimum number of detector positions to uniquely determine the SN location as we will see below. If we add more detector sites such as Gran Sasso and Sudbury, the results would be improved. We note that there is no strong dependence of the results as long as we select four detector locations which are well separated to each other.

We note that ANDES is the first deep underground laboratory in the Southern Hemisphere, which could be constructed in the Agua Negra tunnels that will link Argentina and Chile under the Andes, the world longest mountain range. In the Ref. [22] it is discussed the potential of a neutrino detector at ANDES for observations of SN neutrinos as well as geoneutrinos.

In Fig. 2 we show the solution of Eq. (1) for the case where the SN occurs in the Galactic center, given by α = 17h42m27s and δ = -28°55', for various different combinations of the four detector sites mentioned above. For definiteness, it was assumed that the SN neutrinos arrived at the Earth on March 20$^{\rm th}$ of 2000 at 12:00 UTC but it is straightforward to change this condition.

From this plot, we can see that for a given combination of two detector sites, the SN location can be constrained, as expected, to a closed curve in the sky. It is also possible to see that if we have three different detector sites, we can restrict the possible SN positions to only two locations in the sky. For example, the curves for the Kamioka-South Pole and Pyhäsalmi-South Pole combinations intersect in two locations, the true location of the SN as well as a *fake* solution. If we have detectors at four different sites, it is possible to eliminate the fake solutions and single out the true location in the sky, as shown in [7].

In practice, however, due to the finite resolution of the SN neutrino arrival time measurement, we can only establish the SN direction with limited precision. The accuracy of the determination of θ, the angle between the SN direction and the axis connecting two given detectors, can be roughly estimated as

$$\delta(\cos\theta) \sim \frac{c\ \delta(\Delta t_{ij})}{d_{ij}}. \tag{3}$$

Very roughly speaking, the accuracy of the determina-

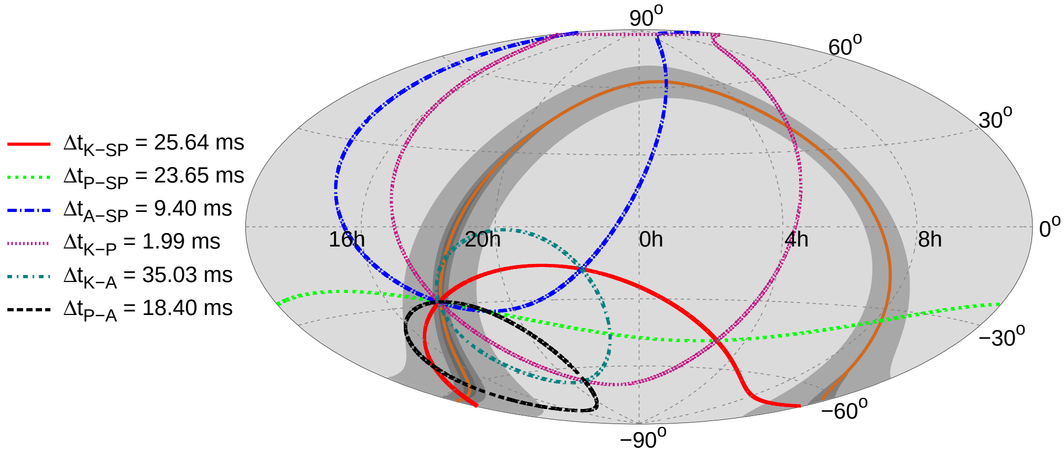

FIG. 2: Possible solutions for the SN direction (α, δ) consistent with a certain difference of the arrival time determined by the combinations of detectors located at two different sites. Here the true (input) position of the SN is assumed to be the Galactic center, with α = 17h42m27s and δ = -28°55'. It is assumed that SN neutrinos are detected at the Earth on the vernal point on March 20^{th}, 2000 at 12:00 UTC. We consider four sites: Kamioka, Pyhäsalmi, ANDES and South Pole, indicated as K, P, A and SP, respectively, in the legend.

tion of the arrival time of SN neutrino signal at a given detector, $\delta t_{\rm arrival}$, can be estimated as [8],

$$\delta t_{\rm arrival} \sim \frac{\tau}{\sqrt{N}}, \tag{4}$$

where τ is the rise time of the arriving SN neutrino signal and N is the number of event that exists in the rising part of the pulse. For the case where the edge is really sharp or if the rising time is considered as zero, it will be

$$\delta t_{\rm arrival} \sim \frac{\tau}{N}, \tag{5}$$

where τ is the duration of the signal and N is the total number of observed events [8].

According to Ref. [17] IceCube alone can reconstruct the signal onset of the SN neutrinos with a resolution of $\pm(1.0 - 1.7)$ ms at 1 σ C.L., depending on the time interval that can be considered post bounce. For a detector like Super-Kamiokande the corresponding uncertainty could be about ± 3 ms [8], but this will depend on the total event rate as well as on the time structure of the SN neutrino signal.

For the case of a failed SN, due to the abrupt termination of the SN neutrino emission, expected by the formation of a black hole, this uncertainty could be further reduced. If the edge is really sharp (similar to the zero rise time case considered in [8]), this uncertainty may be reduced down to 0.3 ms [8], for a detector as large as Super-Kamiokande.

III. COMBINED ANALYSIS

In this section, we discuss the results of our combined analysis by considering observations of SN neutrinos at three and four different detector sites on the Earth.

We define our χ^2 function as follows,

$$\chi^2 = \sum_{i,j} \left[\frac{\Delta t^{\rm obs}_{ij}(\alpha_0, \delta_0) - \Delta t^{\rm theo}_{ij}(\alpha, \delta)}{\sigma_{\Delta t}} \right]^2, \tag{6}$$

where $\Delta t^{\rm obs}_{ij}(\alpha_0, \delta_0)$ is the arrival time difference of SN neutrinos to be observed (expected) for the input (true) SN location in the sky (α_0, δ_0) for the combination of i-th and j-th detector sites on the Earth whereas $\Delta t^{\rm theo}_{ij}(\alpha, \delta)$ is the theoretically expected one for a given SN location (α, δ). $\sigma_{\Delta t}$ is the assumed time resolution. Note that by construction, the best fit values (α, δ) obtained by our χ^2 analysis are the solution of the Eq. (1) for an input value of $\Delta t^{\rm obs}_{ij}$.

In Fig. 3 we show for the same input SN location at the Galactic center used in Fig. 2 what would be the angular resolution for (α, δ) that would result from a combination of arrival time differences registered by three different detectors. For definiteness, we assume, for the combination of two detectors, that the arrival time difference resolution can be $\pm$ 4 ms (left panels) and $\pm$ 2 ms (right panels).

As expected, for all the combinations we considered, we obtained two solutions at different locations in the sky, the true solution and the fake one. We note the true and fake allowed regions are connected at 1 σ C.L. for the cases shown in the lower four panels in Fig. 3. Though we have two solutions, in practice, the one that lay in the region of the Galactic disc has greater probability of being the true one. The fake solution can be eliminated by considering a fourth detector location as we can see below.

In Fig. 4 we show the case where four different detector locations are considered for the same SN input location in the Galactic center for the time resolution of $\pm$ 4 ms (left

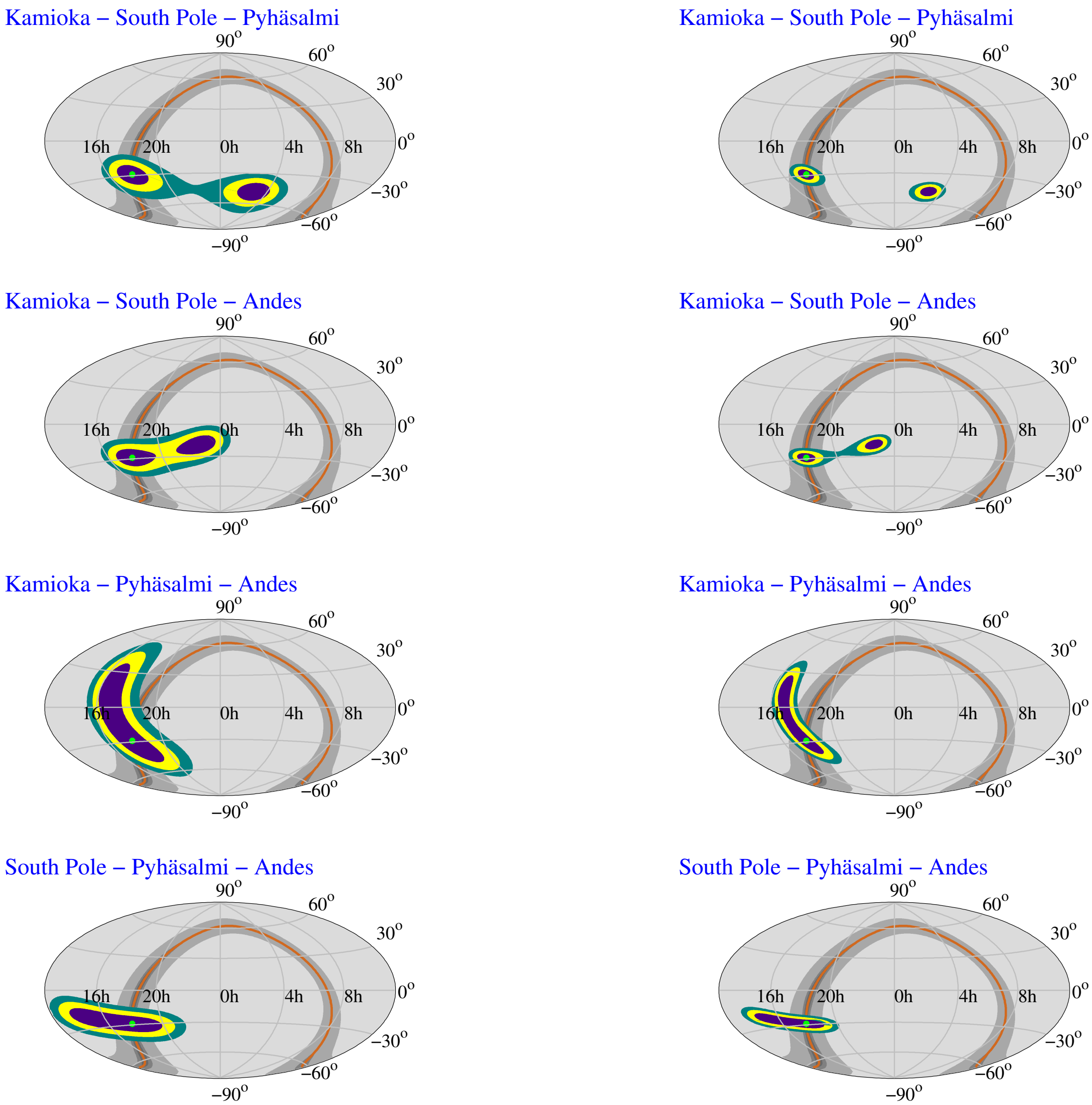

FIG. 3: Cases where three detectors are considered to determine the position of the Galactic SN: Kamioka-South Pole-Pyhäsalmi (first row), Kamioka-South Pole-ANDES (second row), Kamioka-Pyhäsalmi-ANDES (third row), and South Pole-Pyhäsalmi-ANDES (fourth row). Colors of purple, yellow and green indicate, respectively, the regions allowed at 1, 2 and 3 σ C.L.. Here the uncertainty in the time difference measurement between two detectors is assumed to be $\pm$ 4 ms (left panels) $\pm$ 2 ms (right panels).

panels) and $\pm$ 2 ms (right panels). With four detectors at different sites, it is possible to single out the true location of the SN. In Fig. 5 we show similar plots for the case of different SN input location, opposite to the Galactic center, α = 5h42m27s and $\delta = 28°55'$. From these plots we can conclude that the expected precision is $\Delta(\alpha) \sim 15(8)^\circ$ and $\Delta(\delta) \simeq 10(5)^\circ$ for the time resolution of $\pm$ 4 ms (2 ms).

IV. CONCLUSIONS

The era of high-statistics neutrino detectors has started. IceCube is already operating in the South Pole and in a decade or so we expect to also have Hyper-Kamiokande in Japan as well as one very large neutrino detector in the future European underground laboratory in Pyhäsalmi, and there is also a possibility to construct a new neutrino detector at ANDES. This makes the determination of the angular position of a nearby SN by comparing the arrival time of the first SN neutrinos at these different detector locations on the Earth an interesting possibility.

The time resolution of the triangulation technique will be dominated by the smallest detector, since the precision of the reconstruction of the neutrino signal onset depends on the number of neutrinos registered by the detector (see Eqs. (4) and (5)). We have demonstrated that, in

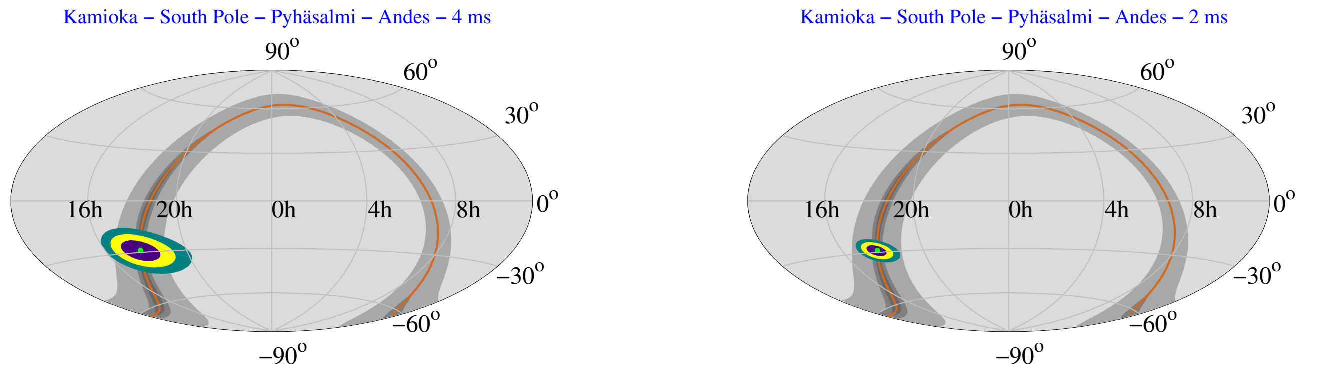

FIG. 4: Allowed regions at 1, 2 and 3 σ C.L. compatible with the combinations of the arrival time differences assuming four detector sites of Kamioka, South Pole, Pyhäsalmi and ANDES for the SN at the Galactic center assuming the uncertainty in the time difference measurement between two detectors of $\pm$ 4 ms (left panels) and $\pm$ 2ms (right panels).

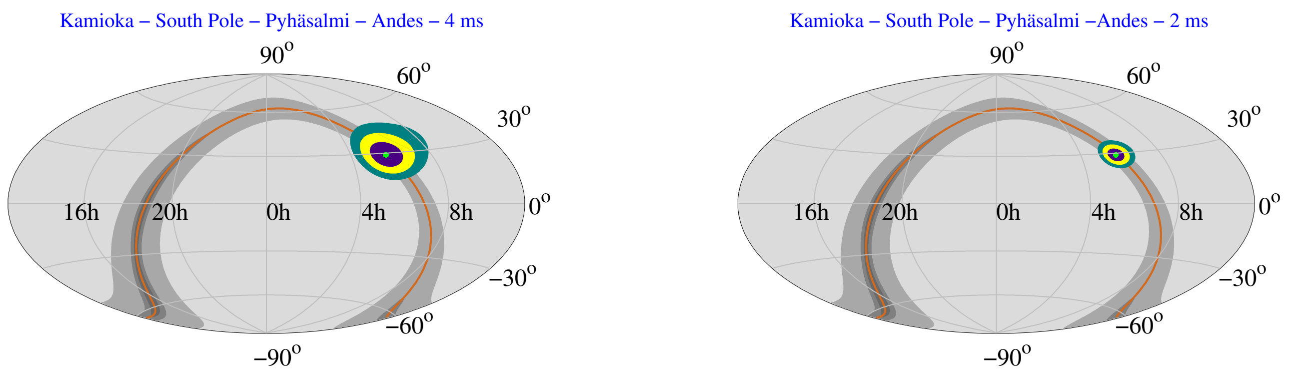

FIG. 5: Same as Fig. 4 but for a SN explosion that occurred at a location opposite to the Galactic center.

general, one needs to combine the timing of four different detector locations in order to uniquely localize the SN using this method.

Assuming a rather optimistic, but not impossible, the uncertainty on the arrival time difference between two detectors to be $\sim \pm$ (2-4) ms, we have estimated the angular resolution of the determination of the location of a SN that could occur in the Galactic center given by four detectors located at the South Pole (IceCube), Kamioka (Super-Kamiokande or Hyper-Kamiokande), ANDES and Pyhäsalmi (LENA, MEMPHYS and GLACIER). We established that in this case the angular position can be known within $\sim 5\ (10)^\circ$ in declination and $\sim 8(15)^\circ$ in right ascension for the time resolution of 2 (4) ms.

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Appendix A: Description of the Equatorial Coordinate System

The SN location can be given in the so-called Equatorial Coordinate System by two angular coordinates, α known as right ascension and δ known as declination. Right ascension measures the angular distance eastward along the celestial equator from the vernal equinox, its is analogous to terrestrial longitude. Usually right ascension is not given in degrees but rather in sidereal hours, minutes and seconds. The vernal point is defined by where the celestial equator and the ecliptic intersect at $00^{\mathrm{h}}00^{\mathrm{m}}00^{\mathrm{s}}$ and longitude $0°$. By definition the north celestial pole corresponds to $\delta = +90°$, so it is analogous to the terrestrial latitude.

This defines the unit vector $\mathbf{n_0}$, which points in the direction of propagation of the neutrinos arriving at the Earth coming from the SN as

$$\mathbf{n_0} = (n_{0x}, n_{0y}, n_{0z}), \tag{A1}$$

where

$$\begin{aligned} n_{0x} &= -\cos\alpha\sin\delta \\ n_{0y} &= -\sin\alpha\sin\delta \\ n_{0y} &= -\cos\delta. \end{aligned} \tag{A2}$$

Let us assume that a detector positioned at the i-th site on the Earth is localized at a certain time t by the following vector

$$\mathbf{x}_i = (x_i, y_i, z_i), \tag{A3}$$

with coordinates

$$\begin{aligned} x_i(t) &= R_\oplus \cos\phi_i(t)\sin\theta_i \\ y_i(t) &= R_\oplus \sin\phi_i(t)\sin\theta_i \\ z_i(t) &= R_\oplus \cos\theta_i, \end{aligned} \tag{A4}$$

where $R_\oplus$ is the radius of the Earth and θ_i is the latitude corresponding to the position of the detector. The angle $\phi_i(t)$ depends on time and can be given by

$$\phi_i(t) \;=\; \phi_i(0) + \omega\, t - \Omega\, T - \pi, \tag{A5}$$

where $\phi_i(0)$ is the longitude corresponding to the initial position of the detector, ω is the angular velocity of the daily rotation of the Earth and Ω is the angular velocity corresponding to the annual rotation of the Earth around the Sun. The time t refers to the moment of the day the SN explosion occurred ($0 \leq t \leq 24$ h), given in terms of the Coordinated Universal Time (UTC), whereas T, assumed to be common for all detectors, is the time elapsed after the vernal point when the detector received the SN neutrinos.

So, if we have two detectors, say, one at site 1 and the other at site 2, we can, explicitly, write the observed arrival time difference as

$$\begin{aligned} \Delta t_{12} &= (R_\oplus/c)[(\cos\phi_1(t)\sin\theta_1 - \cos\phi_2(t)\sin\theta_2)n_{0x} \\ &+ (\sin\phi_1(t)\sin\theta_1 - \sin\phi_2(t)\sin\theta_2)n_{0x} \\ &+ (\cos\theta_1 - \cos\theta_2)n_{0z}], \end{aligned} \tag{A6}$$

which constrains the possible values of α and δ.

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